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HIGH SPEED EXIT TAXIWAYS.(U)
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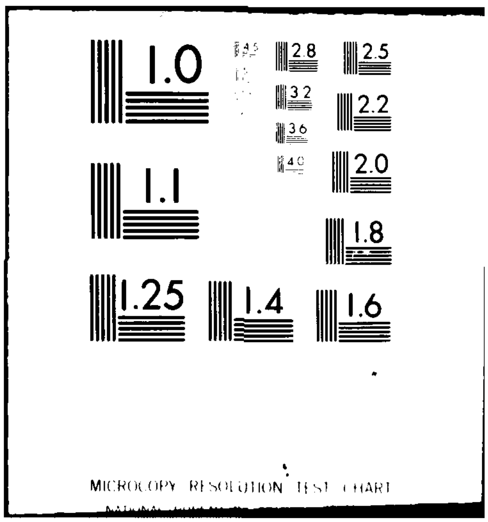
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Report No. FAA-RD-81-16

LEVEL II

(12)

AD A098178

HIGH SPEED EXIT TAXIWAYS

FINAL REPORT

FEBRUARY 1981

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NOTICE

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14

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16. Abstract

The "high speed" runway exit, also known as angled exit, is an airport/airside design feature which can make an important contribution to increasing capacity of the national air transportation system. The present standard angle exit offers a safe and clear reduction in landing time on the runway. However, except in a very few instances, this potential is not realized.

Low utilization of high speed exits, although not conclusively shown, appears to be the results of operational use only where and when need exists to expedite runway clearance. Underutilization also appears to be motivated by desire to avoid any unnecessary risk or passenger discomfort.

Realization of the capacity improvement potential of high speed exits is controlled by the character of the approach control system and the operating procedures currently used by pilots and controllers. Both the average and scatter of current interarrival intervals are sufficiently large to prevent any further benefits from reduced runway time.

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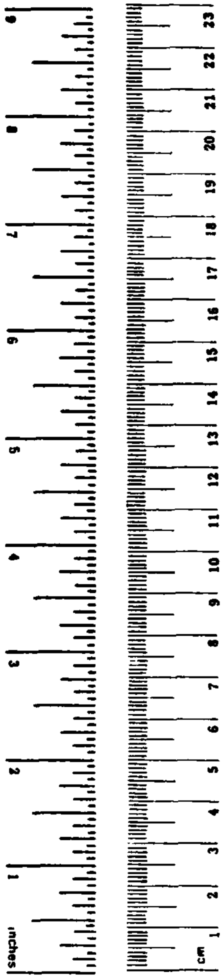
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

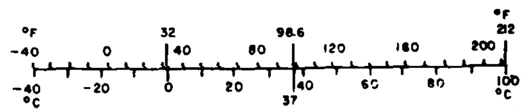
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



60 mph = 52.1 knots (nautical miles per hour)
60 mph = 88'/sec $\quad$ 1g = 32.2'sec^2

1 mph = .87 knots
1 knot - 1.15 mph

ACKNOWLEDGEMENT

This report is an edited version of the work undertaken by Max H. Coggins, Ronald B. Ahlers, and Ed Schaefer.

TABLE OF CONTENTS

FIGURES

Page

FIGURES (Cont.)

Executive Summary

The "high speed" runway exit, also known as "angled exit", is an airport/airside design feature which can make an important contribution to increasing capacity of the national air transportation system. The present standard angled exit offers a safe reduction in landing time on the runway. However, except in a very few instances, this potential is not realized.

Realization of the capacity improvement potential of high speed exits is controlled by the character of the approach control system and the operating procedures currently used by pilots and controllers. Both the average and scatter of current interarrival intervals are sufficiently large to prevent any further benefits from reduced runway time.

Added potential for capacity increases exists if the interarrival interval and runway occupancy time are considered as having high order of dependence and managed accordingly. The current concept of independence between these two variables allows the scatter of both variables to dictate an unnecessarily low landing rate.

Whether user attitudes are any obstacles to acceptance of capacity increasing designs and procedures can only be determined through well planned and executed trials.

1. Introduction:

1.1 Background

Since April 1972, a request has been outstanding for R,D&E effort to develop recommendations for improving criteria for airport planning and design. The subject of the request was "High Speed Taxiways." Taxiway system improvement was identified as a promising approach to reducing runway occupancy and thereby increasing airport capacity to meet growing demand.

The initial response to this request included plans to study improved geometry design criteria, number, location, and operational acceptability of high speed exit/access taxiways with funding for field evaluation.

The high speed exit was selected as the first taxiway element to be studied in order to assess its productivity as an example of a specific attempt to reduce runway occupancy time by airside design standard development. The high speed exit, a 30° turn off the runway with 1800 ft. radius and no specified runout distance, was developed circa 1958 and standardized in the 1960s. A considerable number of them have been constructed on airports throughout the National Airport System.

1.2 Scope/Purpose

This report is intended to summarize the known efforts and findings which are believed pertinent to achieve increased runway capacity through improved airport/airside configuration. Emphasis is placed specifically on the high speed runway exit as a promising design standard. The aircraft ground movement, loading, service and storage functions, and the capability features such as length, strength, etc., of the airport/airside have been ignored except as they may affect the runway operational rate.

The purpose of this report is to provide an approach to airport/airside design standard development and selection which will be more effective in facilitating aircraft operations. Therefore, the report will address the following questions:

(a) Is the information in hand suitable for defining an improved standard and can the potential benefits be assessed with confidence?

(b) What conclusions can be drawn from the existing information to indicate design changes needed?

(c) What additional information is needed to validate the predicted utility of a design change?

(d) What must be done to obtain effective utilization of promising airport/airside designs and how can it be accomplished?

2. Data Evaluation:

2.1 Information Sets

Data from several sources were examined to provide the basis for this report. The data ranged from original field logs and magnetic tapes of unreduced event time records to processed data in graphic and tabular report formats. The data included quantitative records specifically applicable to statistical analysis of operational intervals as well as qualitative information from surveys of pilot/controller viewpoints. Specific sources were as follows:

2.1.1 Data tapes produced under Douglas Aircraft Co. contract for the development of improved techniques for measurement of airport capacity and delay. Threshold crossing and runway clearance times (of day) by aircraft type were observed and recorded during 1973 under both IFR and VFR, as available, at 18 airports (ATL, BNA, BOS, BUF, DEN, DFW, IAD, IAH, LAX, LGA, LVK, MSY, ORD, SEA, SFO, SMO, SNA, TPA). (Ref. h)

2.1.2 Two British reports DORA 7001 and 7502 (from years 1969 and 1972, respectively) provided reduced data on ground operations and runway occupancy times observed at Heathrow Airport. The 1972 observations included Boeing 747 aircraft. (Ref. h)

2.1.3 A report by Howard, Needles, Tammen & Bergendoff under contract DOT-FA71 WA1-218, May 1975, which provided reduction of data collected at ATL, DEN, and ORD to show exit speeds, runway occupancy times and variation thereof by aircraft type. (Ref. d)

2.1.4 The NASA Langley Terminal Configured Vehicle (TCV) program conducted aircraft operational tests, collected data, and performed analysis to demonstrate the feasibility of markedly increasing the air carrier aircraft arrival acceptance rate of suitably designed airport runways. Tests were aimed at identifying the acceptable range of exit speeds, radius of turn, and cornering accelerations using the TCV Boeing 737 airplane. (Ref. i&j)

2.1.5 A series of threshold crossing time records made at ORD in 1976 to assess the potential benefits of wake vortex advisory equipment. Original, unreduced data logs of threshold crossing times covered as long as 7 hours continuous operation. (Para. 3.3.1) (Figure 9)

2.1.6 An opinion survey, partially reduced, from interviews conducted with pilots, airline management, and tower/traffic control personnel regarding landing and ground operations at ORD, ATL, DFW, and DEN. (Ref. h)

2.2 Information Selection

The information utilized in generating this report consisted almost entirely of data previously collected, reduced, and examined for a variety of purposes. In re-examining the data, an attempt was made to select and present only those facts which would contribute to identifying the causes of, and possible corrective measures for, poor performance of high speed exits. To do this, a set of simplified hypotheses were postulated to serve as guideline for sifting out the pertinent data. It is important to determine whether there are existing facts to substantiate these current views, facts to deny them, or if they are simply unfounded and additional investigation is required. These guidelines for data sampling are stated as follows:

(a) Design flaws and/or omissions in the high speed exit standard cause the poor utilization and if the necessary corrections are made, operational use will become compatible with the design expectations.

(b) Pilot skills and/or aircraft capabilities are the primary factors limiting high speed exit utilization.

(c) Air traffic control separation standards and practices, both present and currently planned, produce interarrival intervals too large to permit any increase in runway capacity to result from reduced occupancy now or in the forsceable future.

Unfortunately, using a, b, and c as independent guideline criteria does not give a satisfactory coverage. For example, (a) must be based on the constraints which might be identified by (b) and also operationally acceptable limits identified by investigation. Therefore, the guidelines must be considered in combinations to obtain an effective data sampling.

2.2.1 Exit Design Criteria

The design features for the present exit standard appear to have been almost entirely developed under the project reported by R. Horonjeff in reference (a). Empirically determined values for acceptable lateral accelerations (figures 1a, 1b), turn radii, total turn angles and visual cueing were reviewed in references (a), (b), and (c), along with the techniques used to develop them. Updating information was provided by test results from the 737 airplane test exiting performed by NASA Langley's Terminally Configured Vehicle (TCV) program. No effort was applied to examining such details as width, filleting, strength requirements, etc. To identify runway clearance parameters, aircraft dimensional data was obtained from various manufacturer's aircraft characteristics--airport planning data documents. (Ref. i&j)

2.2.2 Data on Pilot/Aircraft Constraints

The data needed to determine whether limits on pilot skills, passenger discomfort/disorientation or aircraft capabilities such as structural or ground handling limitations were significant factors was not immediately available in the detail desired. However, data from the original development report (Ref. a) direct contacts with aircraft manufacturer's specialists (Boeing Co.) and demonstrations by the Terminally Configured Vehicle program' SB737 were utilized and were considered adequate for the purpose of this report.

2.2.3 Data on Approach Separation vs. Runway Occupancy

The only data set which allowed correlation of approach separation with runway occupancy intervals was the DAC/PMM data collected circa 1975. Other bits of data which helped identify distribution parameters were the British reports and the ORD observations made for WVAS. The DAC/PMM data was useful for picking out samples of maximum and minimum intervals, variation between lead/trail pairs of different size aircraft. The WVAS data provided a basis for comparison of visual vs. non-visual clearance separations. Data for future projections included UG3RD performance estimates by MITRE, and calculations of short-term possible landing operation improvements. (Ref. e)

2.2.4 Basis for High Speed Exiting as a Requirement

The needs for increased runway capacity were expressed by a wide variety of Agency reports and statements. See references (f) and (g). The ability of high speed exiting to contribute to increased capacity was taken from calculations made by the author and others, particularly the NASA TCV project and MITRE. Information to estimate the likelihood of high speed exiting becoming accepted and utilized as a standard operational practice was obtained from reference (d).

3. Analysis and Concept Development

The operational utilization of high speed runway exits is subject to the unilateral views and actions of so many separate groups it is believed important to address certain parts of the subject separately as much as possible. The breakdown selected is (1) the design standards, (2) physical constraints, (3) traffic control interaction, and (4) analysis of requirements. Unfortunately, detail examination of a single phase of a subject is likely to create a biased or faulty concept of the subject as a whole. This may have been the reason such poor utilization resulted from such a promising scheme. In order to avoid the same trap, special attention will be given to the influence of interacting specialty areas.

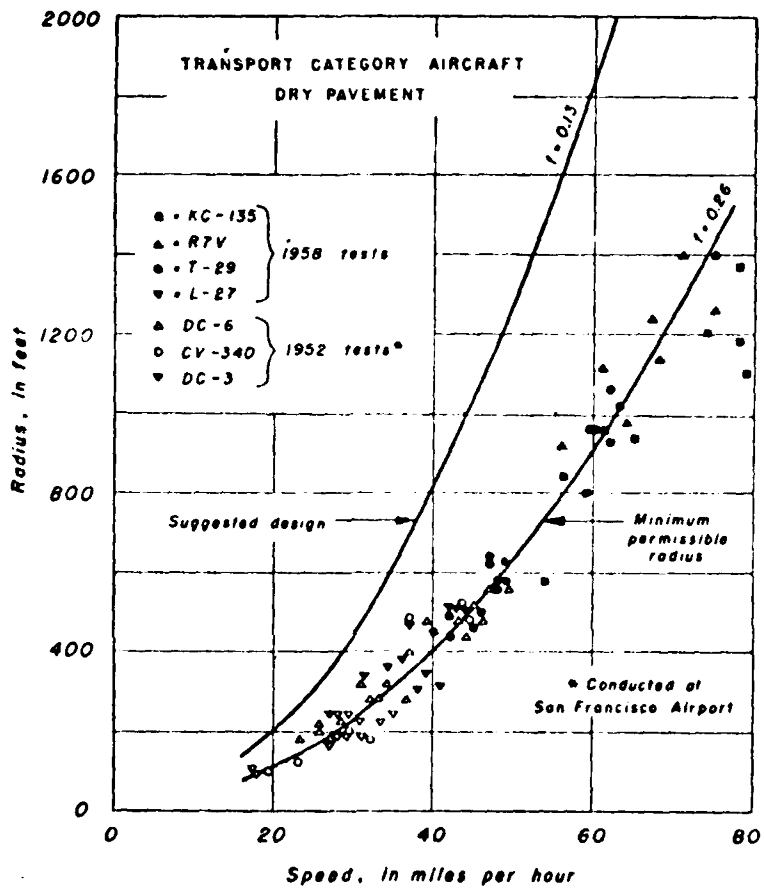
3.1 The High Speed Exit Design

The approximately 190 high speed, lighted runway exits in existence today on U.S. airports were constructed generally, if not fully, in compliance with the FAA design standard AC 150/5335-1A, ref. (b). If any of these standard design features or omissions therefrom can be shown responsible for low exit utility then corrective revisions should be developed. Unfortunately, when some design feature is strongly suspected, it does not necessarily follow that an apparently obvious cure will prove successful. The utility of design is eventually dependent upon the user as well as the ability of the designer to predict the user's techniques. It is believed that the primary design features of a runway exit important to the way it can be used (besides strength, width, and filleting) are (1) the turn radius, (2) the turn magnitude, (3) the visual cueing, and (4) the use consequences. All of these tend to interrelate so that there can be several equivalent sets. However, each involves a separate design decision item and will be discussed separately.

3.1.1 The Turn Radius

The present FAA design standard, reference (b), specifies a basic exit centerline radius of 1800 feet. The initial point of curvature is preceded by a 200-foot strip offset 3 feet from the runway centerline. The offset is comparable to an initial larger radius sector for a gradual entrance to the turn (figure 2). The ICAO standard keeps this feature as a 5-degree initial turn with a 3200-foot radius continuing into the remaining 25 degrees of the turn at a radius of 1800 feet (figure 3). The provision of a compound turn off centerline for gradual turn entrance may be considered as an allowance for the initial application of turning torque to establish the angular velocity of the aircraft in the turn. However, in view of the generous width of the runway and taxiway and ample edge fillets, the available allowance for wide variance in turning techniques makes the need for precise centerline definition as a track somewhat trivial. The airplane pilot has considerable latitude in the way he chooses to make a turn; e.g., over steering to under steering the centerline and gradual or sharp lead into the curve. The centerline initial curving, marking, and lighting is primarily a matter of provided cues as to exit location, turn sharpners, etc., rather than a precise path definition. While proper cueing is very important, it should not be considered a constraint in developing the turn radius or determining an optimum value.

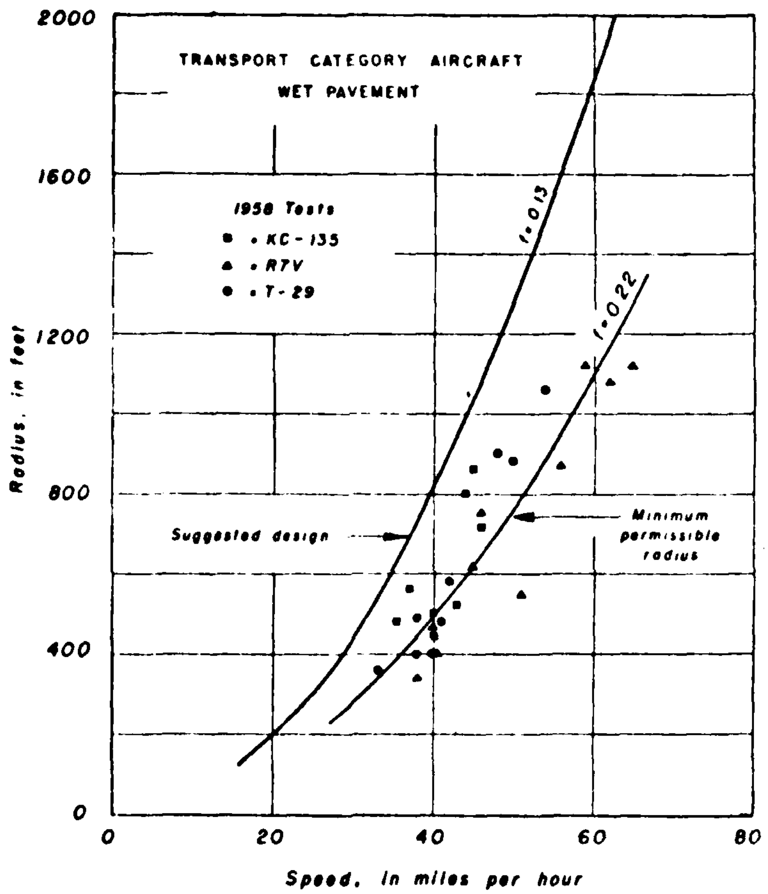
The present turn radius of 1800 feet was selected as a result of the development efforts reported in reference (a). From a number of exit operations run at speeds ranging 20 to 80 mph (17.5 to 69.5 knots), the acceptable speed vs. turn radius appeared, with some variance, to follow a constant radial acceleration parameter of about 0.26 gravity (8.36 ft/sec^2). See figures 1a and 1b. The suggested parameter value for design was 0.13g since this provided a reasonable safety factor for aircraft types and pavement conditions tested. In translating the recommendation to a standard the parameter



Note: Pilot assessment of maximum cornering capability correlates closely with constant lateral acceleration and averages about half of available lateral force--see Fig. 7c.

Source: Reference (a).

Figure 1a. Radius vs. Speed; Transport Category Aircraft; Dry Pavement



Source: Reference (a).

Figure 1b. Radius vs. Speed; Transport Category Aircraft; Wet Pavement

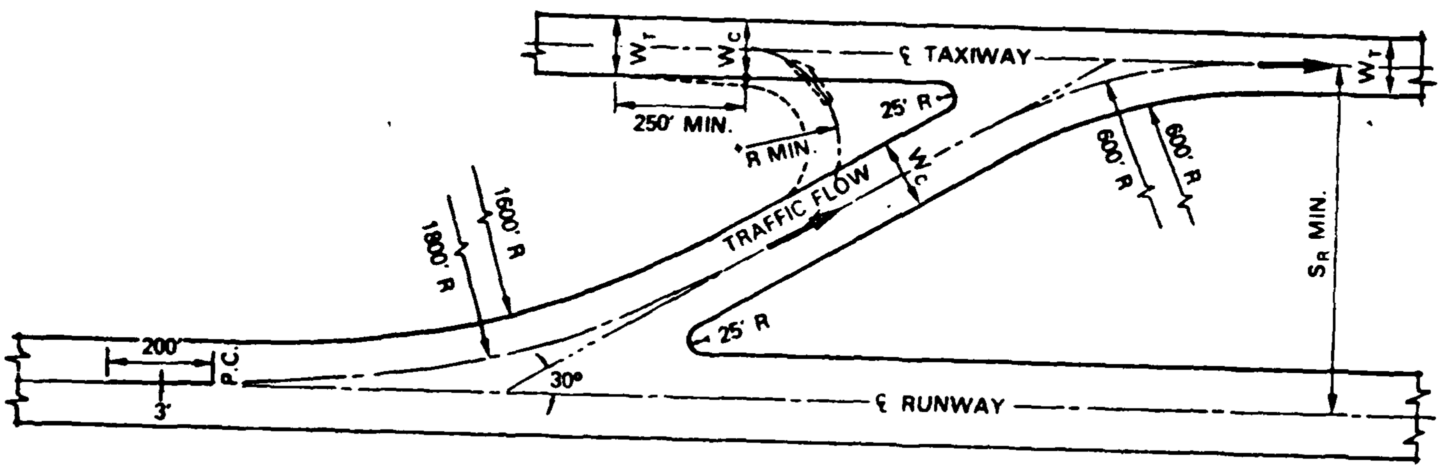


Figure 2a. **ANGLED EXIT TAXIWAY DESIGN**

Source: Reference (b).

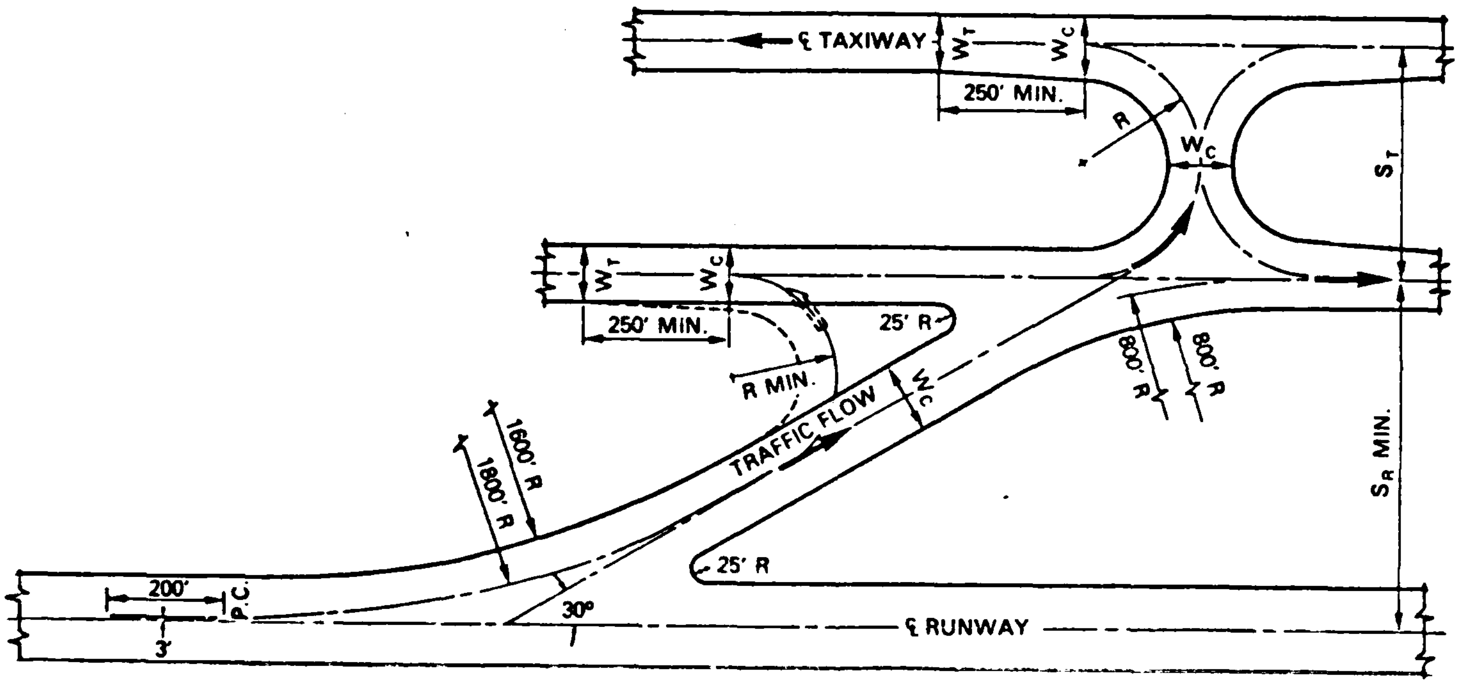
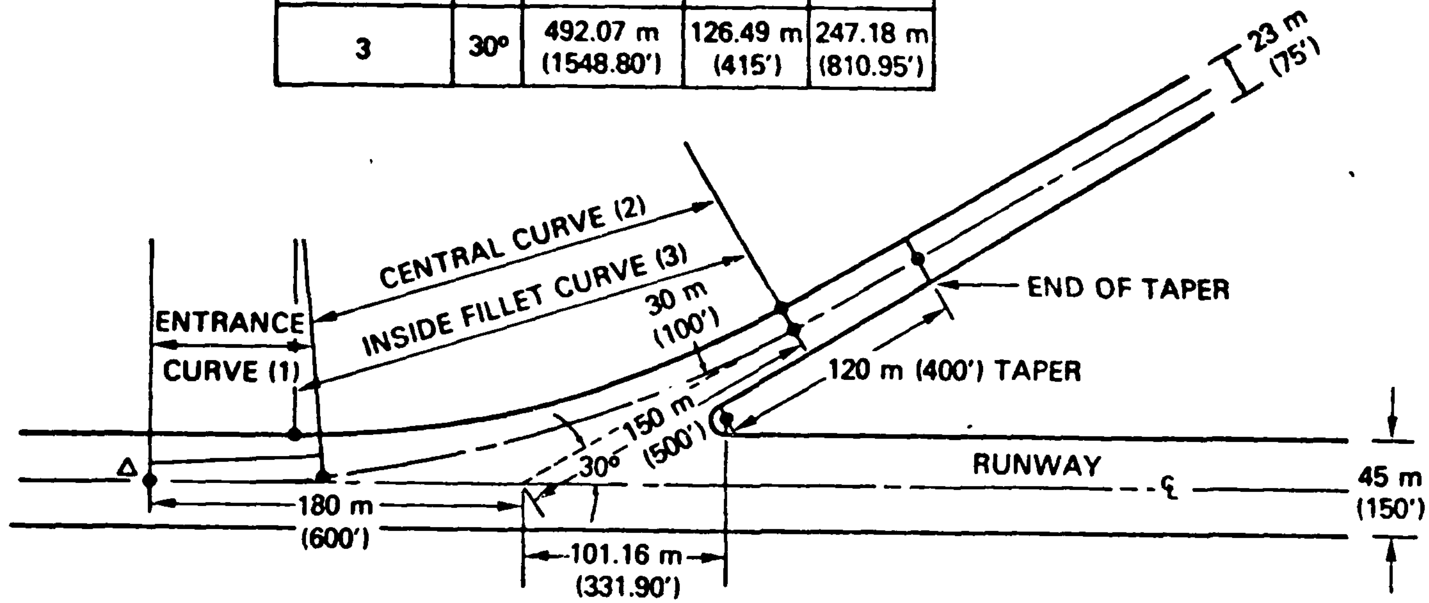


Figure 2b. **ANGLED EXIT TAXIWAY DESIGN WITH DUAL PARALLEL TAXIWAY AND CROSSOVER**

Source: Reference (b).

CURVE NO.	Δ	R	T	L
1	5°	977.37 m (3206.60')	42.67 m (140')	85.29 m (279.83')
2	25°	556.82 m (1826.85')	123.44 m (405')	242.96 m (797.11')
3	30°	492.07 m (1548.80')	126.49 m (415')	247.18 m (810.95')



IN THE BOX Δ IS THE CURVE ANGLE, R THE RADIUS,
THE TANGENT LENGTH AND L THE LENGTH OF CURVE.

STANDARD DESIGN FOR HIGH SPEED EXIT TAXIWAYS ICAO DOCUMENT 9157-AN/901 PART 2

Figure 3.

was allowed to grow slightly to 4.30 ft/sec^2 so that an 1800-foot radius was rated at 60 miles per hour (62.1 Knots). Sharper turns were given reduced speed ratings to maintain the same radial acceleration of 4.3 ft/sec/sec as shown in appendix 1, page 9 of reference (b), the exit standard.

Observations indicate that for most air carrier airport operations pilots are turning off the runway at considerably less than 60 mph exit design speed. In fact, average exit speeds at busy airports are averaging about 70 percent design speed which is equivalent to half the design lateral acceleration. This would indicate that if lateral acceleration is the critical parameter, present air carrier operations desire about half the level found acceptable under reference (a) tests. If current operating practice is accepted as design criteria, then the 1800-foot radius provides about 40-mph exit rather than 60. Perhaps if the radius was increased to 3500 feet and current practice maintained, the 2.21 ft/sec^2 (.07g) lateral acceleration 60 mph exiting would actually result. Clearance time differences calculated for two exits, two runway widths, and six current aircraft are shown in figure 4a and the clearance basis geometry shown in figures 4b and 4c. The high speed exit shows an advantage in lower runway occupancy time of 12½ and 14½ seconds.

The time interval model shown in figure 6a breaks the landing into five time intervals, which permits applying attention to results obtainable from each part. A typical velocity/time profile as in figure 6b shows that runway occupancy time

Figure 4a. Time Savings--High Speed Exit (30° Turn) vs. Normal Exit (90° Turn)

A/C	Runway Width	Taxi Distance to Clear Edge of Runway From IPC @ 90° Turn 250' Radius ($S_{90}=L_{90}+X$)	@ 30° Turn 1800' Radius ($S_{30}=L_{30}+Y$)	Time Ratio $\frac{t30}{t90}$	Time t90 @20K	Clearance Time Savings at Same Lateral Acc. Δt	Clear & Decel. Time Saving By HSE
DC-9	150	324	681	.783	9.6	2.08	13.41
	200	357	763	.797	10.6	2.15	13.48
737	150	299	668	.833	8.9	1.49	12.82
	200	332	750	.842	9.8	1.55	12.88
727	150	331	712	.802	9.8	1.94	13.27
	200	365	794	.811	10.8	2.04	13.37
707	150	352	754	.798	10.4	2.10	13.43
	200	385	836	.809	11.4	2.18	13.51
DC-10	150	381	788	.771	11.3	2.59	13.92
	200	414	870	.783	12.3	2.67	14.00
747	150	429	846	.735	12.7	3.37	14.65
	200	462	928	.749	13.7	3.44	14.77

Clearance
Time Savings = Δt

$$\Delta t = t_{90}\left(1-\frac{t_{30}}{t_{90}}\right)$$

$$\frac{t_{30}}{t_{90}} = \frac{S_{30}}{S_{90}} \cdot \frac{V_{90}}{V_{30}} = \frac{L_{30}+Y}{L_{90}+X} \cdot \frac{V_{90}}{V_{30}}$$

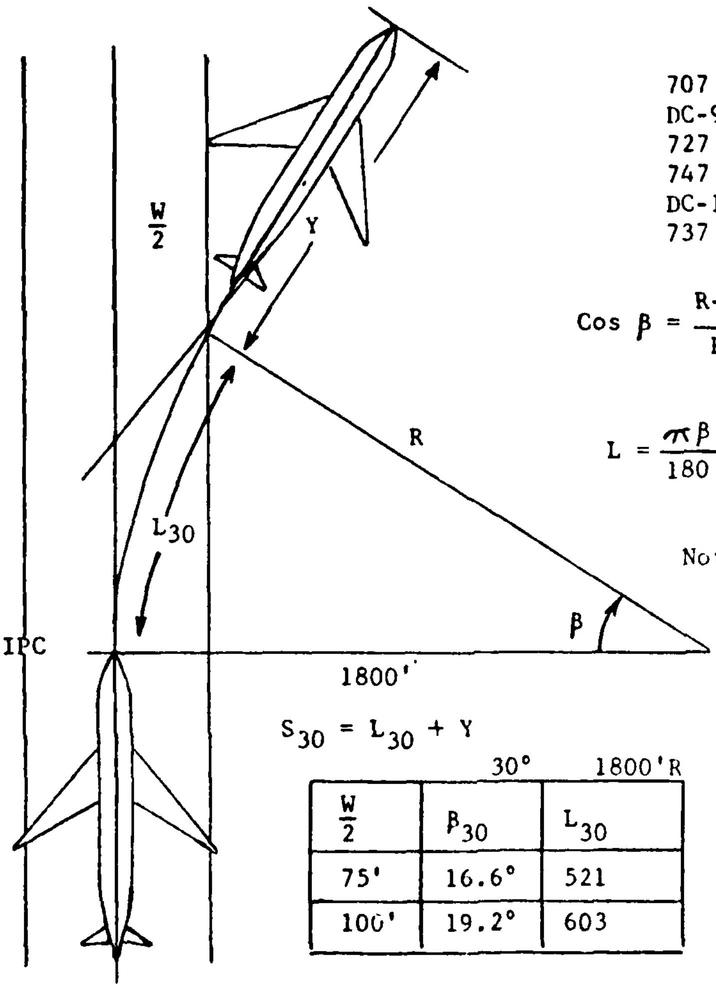
For same accel. $a = \frac{V_{90}^2}{R_{90}} = \frac{V_{30}^2}{R_{30}} \therefore \frac{V_{90}}{V_{30}} = \sqrt{\frac{250}{1800}} = .373$

Deceleration Time Savings

$$= \frac{V_{30}-V_{90}}{a} = \frac{(53.6^k-20^k)\ 1.689}{5'/\text{sec}^2} = 11.33 \text{ secs.}$$

(1k/hr = 1.689'/sec)

Clear. & Decel.
Time Savings = Δt + 11.33 seconds



	Length X	Length Y
707	153	233
DC-9	125	160
727	133	191
747	230'	325'
DC-10	182'	267'
737	100'	147'

$$\cos \beta = \frac{R - \frac{W}{2}}{R} = 1 - \frac{\frac{W}{2}}{R}$$

$$L = \frac{\pi \beta}{180} R$$

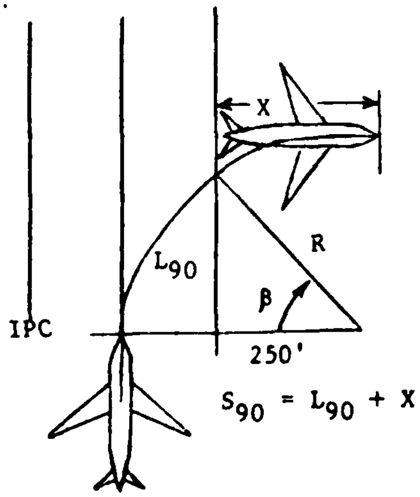
Note: Wing is last to clear.

$$S_{30} = L_{30} + Y$$

30° 1800'R

$\frac{W}{2}$	β_{30}	L_{30}
75'	16.6°	521
100'	19.2°	603

Figure 4b. **Taxi Distance to Clear Runway Edge--High Speed Exit (30° Turn)**



$$S_{90} = L_{90} + X$$

90° 250'R

$\frac{W}{2}$	β_{90}	L_{90}
75'	45.6	199
100'	53.1	232

Note: Tail is last to clear.

Figure 4c. Taxi Distance to Clear Runway Edge--Normal Exit (90° Turn)

Deceleration and runway clearance penalty in seconds from using 30 knots vs. 60 knots exit speed on high speed exit (900 ft. to clear)

Deceleration Ft/Sec^2	Deceleration Penalty Sec.	Lower Taxi Speed Penalty Sec.	Total Penalty Sec.
4	13	9	22
5	10	9	19
6	8	9	17
7	7	9	16
8	6	9	15

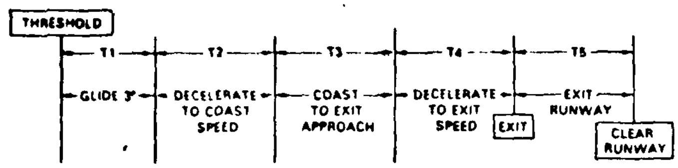
Note: Runway occupancy time is particularly sensitive to taxi/exit speeds.

Figure 5. High Speed Exit Utilization (Penalty) of 30 Knot vs. 60 Knot Speed

is not likely to vary greatly from that determined by the average of the over-the-threshold and exit speeds and the distance threshold to exit. The speed/distance profile of figure 6c shows the potential saving of 60 plus seconds runway occupancy time by flying instead of taxiing over the unneeded portion of the runway. Where there is no particular effort to reduce runway occupancy time the level varies excessively and appears to be proportional to the runway distance from threshold to selected exit. It may also be noted that in the real world actual speed/distance profile lie between the two extremes shown in figure 6c. This is shown by the range of runway occupancy time at the specific distance from the threshold of 30 to 60 seconds (figure 7a) as the system currently operates. Figure 7a shows RWOT = DIST/133 + 10, and 7b RWOT = DIST/133. The mean difference of 10 seconds was probably due to exit timing technique differences. This gives a good rule of thumb, 3/4th second per 100 feet of runway used.

The optimum turn-off radius may be influenced by construction cost considerations, a requirement for entrance from both directions, airport geometry, safety margin required, by a compensating design feature or in aircraft cornering limitations. Generally cost limitations indicate smaller turn radii. However, safety is usually the primary consideration so that any operational facility is constructed to be adequate for the most extreme operation condition. For example, according to lateral dispersion studies of aircraft landings (Ref. k, Appendix D&E), a 100-foot wide runway would never be too narrow for landing the widest gear airplane more than one time in 10,000 (likely never with well marked edges). The additional 50- to 100-foot conventional width provides an excellent safety margin for deterioration in directional control, pavement conditions, etc. Runway length also has a considerable safety margin at respectable cost levels. Probably less than 1 percent of normal operations need more than a third of the runway (Ref. d, Appendix D&E), The 1800-foot radius turnoff is certainly feasible. About 77 of the busiest U.S. airports have over 190, even though only about the top 30 airports are busy enough to occasionally reach a reasonable high speed exit utility level.

Three factors contribute to the safety benefits provided by large turn radii. One is the traditional emphasis on achieving adequate high speed "directional stability" in aircraft ground operation to ensure safe takeoffs and landings while placing considerably less emphasis on the ability to enter, hold, and exit high rate turns (cornering). Even with easy nose wheel steering, the small fraction of total weight on the nose wheel prevents tricycle airplanes from being very effective in initiating high turn rate and encourage severe tire scuffing on short radii maneuvers. Tire scuffing at appreciable speeds is unsafe and can be considerably discouraged by providing large radii exits/intersections. Another safety benefit of large turn radii is due to the phenomenon called "yaw angle of a rolling tire under side load" (radial acceleration) and its relation to the turning center. As a vehicle enters a turn,



$$T1 = \frac{S1(0.592)}{V1}$$

$$T2 = \frac{V1 - V3}{A2(0.592)}$$

$$T3 = \frac{S3(0.592)}{V3}$$

$$T4 = \frac{V3 - V5}{A4(0.592)}$$

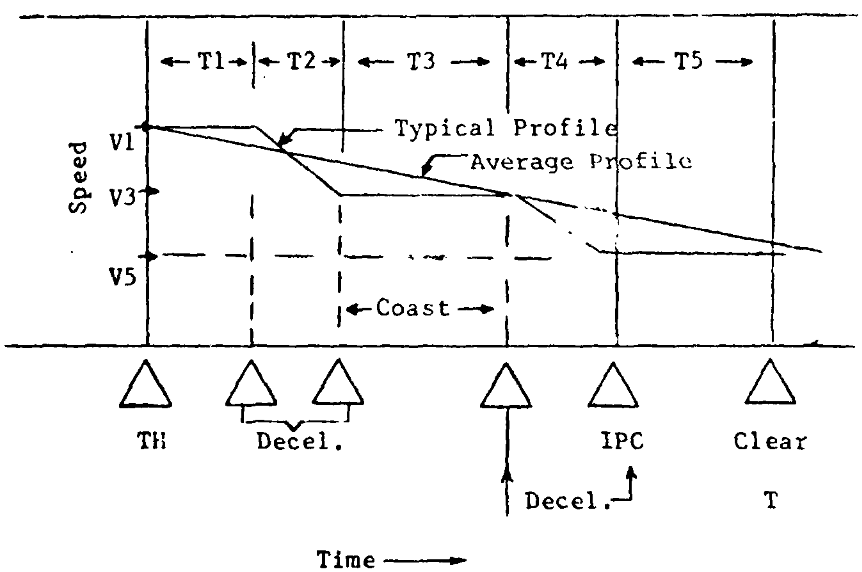
$$T5 = \frac{S5(0.592)}{V5}$$

Arrival runway occupancy time
ARWOT = T1 + T2 + T3 + T4 + T5

Note: Approaches to occupancy time reduction should be directed at specific parts.

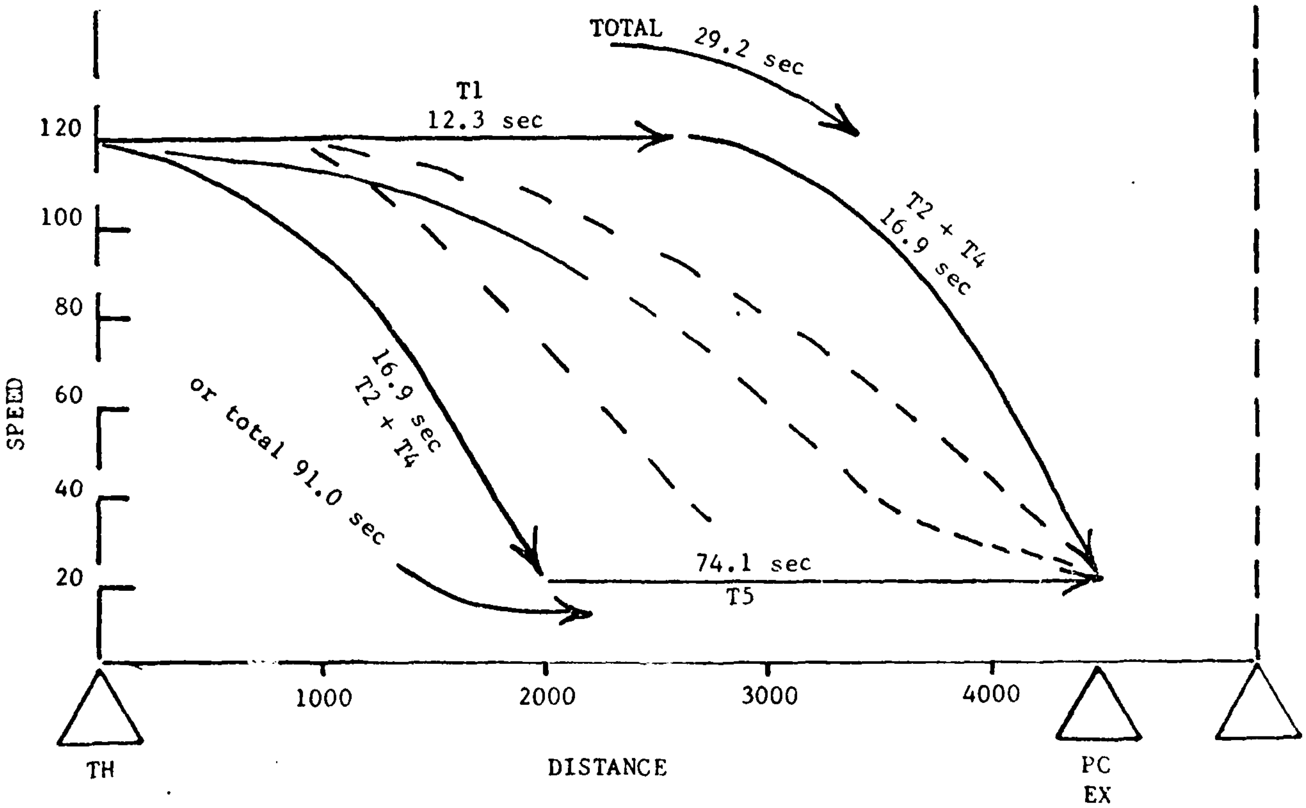
Source: reference (h)

Figure 6a. Time Interval Model (Landing)



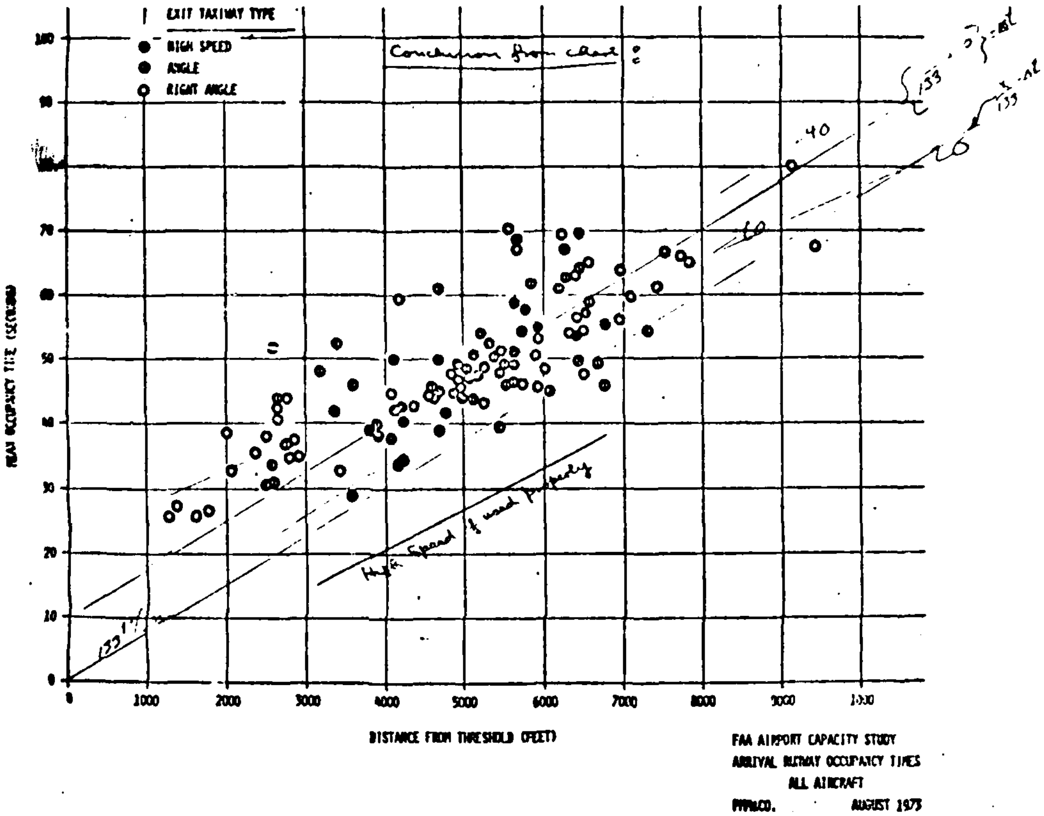
Note: Average occupancy time will correlate with length of runway used.

Figure 6b. Velocity (Speed) Profile (Landing)



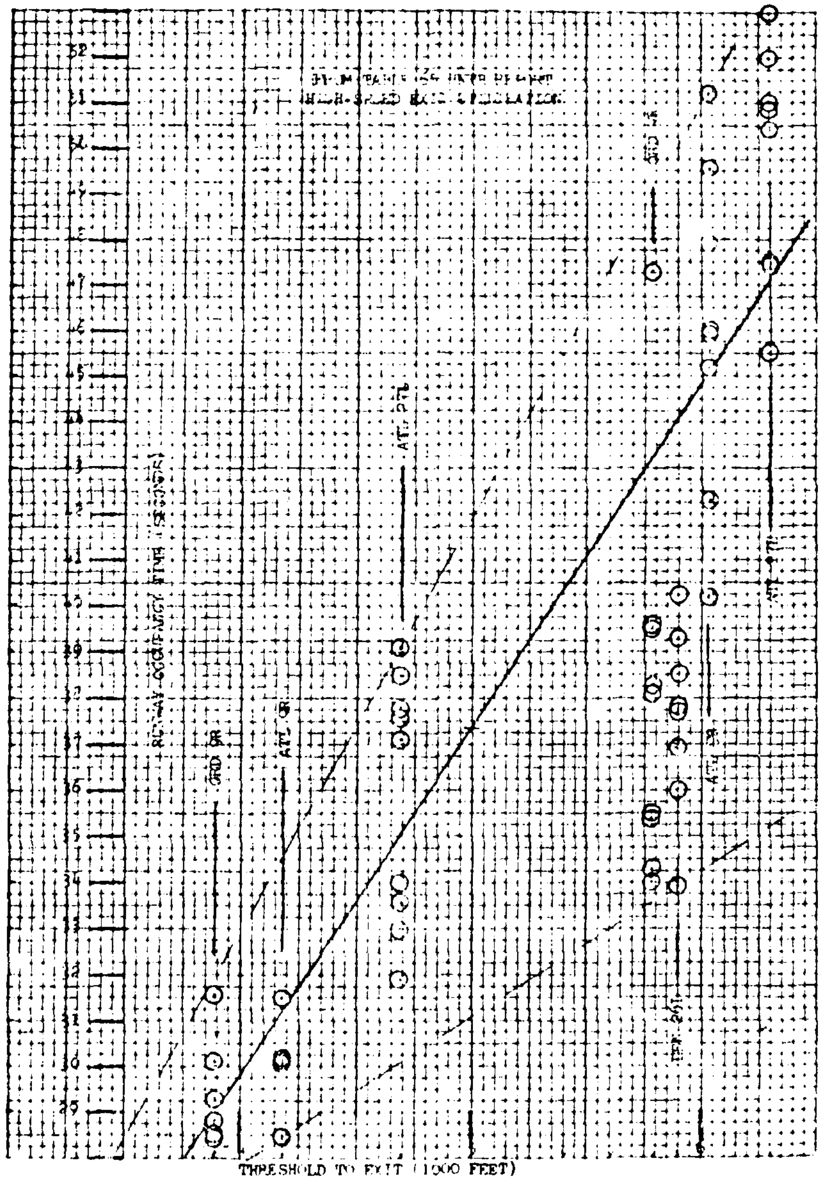
Note: Potential difference in occupancy time on 4300 ft. runway can be approximately 1 minute by avoiding excessive taxi distance before exiting.

Figure 6c. Limits on Speed/Distance Profile Provided by Early & Late Braking With Same Deceleration



Note: Approximate standard error is only 6 seconds from 3/4 second occupancy time for each 100 ft. of runway used for all types of aircraft and exits.

Figure 7a. Runway Time vs. Distance Data--PMM&Co., 1973



Note: Confirms findings of 7a.

Figure 7b. Runway Time vs. Distance Data--Table 65--HNTB, 1974

Source: Reference (g) (Table 65)

the turning radius decreases, the tires accept lateral load, increasing their yaw angle, the turn center moves forward, steering corrections may require reversal, etc. (a generally difficult dynamics problem), so that variations in the actual track may be considerably different than intended. Short turn radii encourage variance in turning tracks and are associated with tire scuffing. (For further discussion see para. 3.2.1.) Sixty knots on a 1800-foot radius is a gentle 3.18-degree per second turn giving about the same visual motion cues as a standard rate turn (3^o/sec) which has been considered for years to be an effective yet low stress IFR maneuver. The third safety feature associated with keeping runway exit radii as large as possible is the "reduction of independence" between the interval of time an airplane is on the active part of the runway and the following interarrival interval. Simply, when a following aircraft is close, the lead aircraft can be expected to expedite runway clearance and most effectively if a high speed exit is available. This is a decided advantage in avoiding missed approaches and also avoids all approach spacing having to exceed the longest likely runway occupancy time. If the two time intervals could be made completely dependent and if there were no other separation restrictions, runway capacity could be at least doubled. (Details discussed in para. 3.3, 3.3.1, 3.3.2, 3.3.3).

3.1.2 The Turn Magnitude

The standard, reference (b), encourages by sketches, but does not specify, a 30-degree turn off the runway for the 1800-foot radius high speed exit. There is a great deal to be said for the operational advantages of a short turn over a long turn. The short turn allows much greater advantage to be taken of pavement width and filleting to vary turning techniques, even to accomplishing distinctly shorter or longer turn radii. However, the purpose of a curved pavement is to change travel direction from some initial heading dictated by wind or traffic control to a heading that leads to the desired destination so that where traffic efficiency is a consideration the exit turn magnitude would be sized to a specific need. Examination of several airport layouts indicate that this application is rare. In most cases the exit turns 30 degrees into a straight taxiway over to the parallel taxi strip as if it were intended to be an alternate landing roll-out strip with a 150-degree turn likely at the end. The length varies with spacing of the runway/taxiway giving about 1000' from initial point of curvature to a hold clear position. This distance is generally adequate for entering at 60 knots except when pavement conditions are poor or a hold clear, stop, or sharp turn are required. Shortening the turn would provide more runout but would require greater clearance travel distances at both ends.

The results of reference (a) indicated that negotiation of 30-degree and 45-degree turns were equally safe but indicated that shorter "sight distance" made the 30-degree turn preferred. From the indicated optimum radius of 1800 feet and the sharp reduction in runway clearance rate afforded by lesser turn angles the 30-degree turn is most likely the minimum acceptable. If the operating concept using an alternate roll out strip is abandoned, as it appears to have been, then larger turn angles to accommodate easier access to the taxiway network will contribute to improved airside capacity. Each exit should be evaluated with respect to an optimum traffic pattern for the specific airport.

Runway 27R at O'Hare has a good example of a practical exit which leads directly into the "beltway" around the terminal dock area.

3.1.3 The Visual Cueing

An entire advisory circular is devoted to centerline marking and lighting of taxiways including runway exits, reference (c). Reference (a) also reported considerable investigation into this aspect of runway exit design and usage. It appears that the present lighting and marking standards used are adequate for cautious use by pilots familiar with the general airport geometry. The present lighting and marking provide the pilot good indication of exit locations but there is no cueing as to the best exit to take or whether he is approaching the best exit with a deceleration program that will reach the exit with best speed for exiting. This discrepancy may be the primary cause of low utilization of high speed exits.

The conventional air carrier landing/exit operation usually involves sufficient experience and familiarity with the airfield that there is no question as to which exit will be used. Prudence dictates that the exit be taken at an acceptably low speed and that the assurance is very high of decelerating to the acceptable speed by the time the exit is reached. In the absence of a precision deceleration technique a generous allowance is made for possible underestimating and considerably longer than necessary average time on the runway results.

3.1.4 Exit Use Consequences

Studies have indicated that time on the runway and exit usage are strongly influenced by both risk and convenience considerations. If there is no obvious risk differential, the choice is the most convenient; usually the shortest, least inhibited route to the loading dock. Traditionally, on an air carrier airport all conventional maneuvers are kept to such safe procedures that risk ceases to be a consideration. Therefore, access to short distances, fewest intersections, paths with clear right-of-way, generous turn radii, etc., primarily determine exit selection. The speed at which the exit is taken may be lower than ordinarily considered

acceptable if the available runout distance seems short due to poor pavement surface conditions.

3.2 The Physical Constraints

The design characteristics and resultant usages of a high speed exit may be limited by certain physical limits on capability (aircraft/pilot). The first to come to mind are the capability of the landing gear to withstand safely the necessary side loading and the skill of the pilot to negotiate the turn. These are additionally impacted by the character of tire/pavement reaction, the stability and control response of the airplane steering system, and the judgment and motivation of the pilot.

3.2.1 Airplane Limitations

Strength sufficient to accept the maximum side load that can be produced by tire to ground surface reaction appears to be universal landing gear design practice. This does not necessarily include ability to survive striking a curb or ditch in a side skid but no evidence could be found that any side load produced by pavement friction on a tire would cause an airplane structural problem.

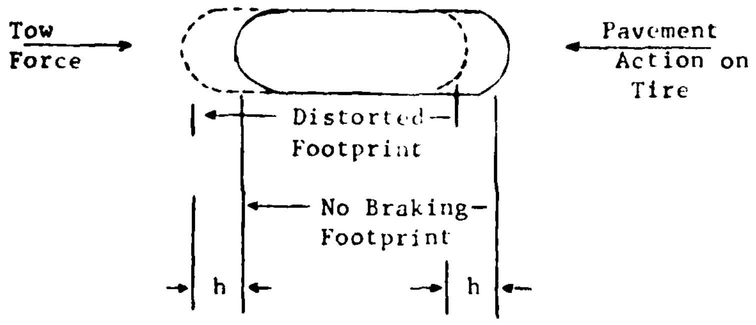
The feature important to exiting and exit design is the reaction obtainable from friction between the tires and pavement. The magnitude of the reaction obtainable is determined by pavement surface condition, tire performance, brake system effectiveness, load on the tire, and speed. A locked wheel at zero speed on a good dry, concrete surface can resist movement by a force approximately equal to the load; i.e., coefficient of friction, ratio of the tangent to normal force of about one. (In most aircraft design, coefficient of friction (u) = .8 is considered for dry concrete or asphalt. Unfortunately, the locked wheel, zero speed condition has little application to runway exiting either for the deceleration from touchdown speed or for the cornering during turnoff. The physical phenomenon which produces the pavement to rolling tire tangent force during braking and cornering involves stretching or twisting the portion of the tire in contact

with the pavement. As the tread initially contacts the pavement, it is essentially undistorted; then it is progressively stretched (laterally for cornering and aft for braking) until it leaves the pavement and relaxes or the stress exceeds the friction force and scrubbing begins. At the point where scrubbing is ready to begin, the total reaction force is maximum. Either side of the optimum tire/pavement relative motion (percent slip for braking, yaw angle for cornering) the reaction force is reduced. With harder braking/cornering a progressively greater fraction of the footprint scrubs. Since scrubbing friction is considerably less than sticking friction, the available reaction force decreases to the level provided by 100 percent scrubbing as in a locked wheel or full side skid. See the simplified friction models in figures 8a,b,c, and d (developed specifically for this report). However, the scrubbing state of braking and cornering is easily entered during high performance operations and is not particularly obvious to the operator. Avoiding scrubbing is most easily accomplished by avoiding heavy braking or cornering. The greatest average operational braking or cornering acceleration that should be expected is about 8 to 5 ft/sec^2. When pavement conditions are poor, as with water, snow, ice, rubber contamination, etc, the operational friction stopping and cornering capability can easily be reduced another 50 percent or more.

The optimum percent slip and yaw angle for maximum braking and cornering depend on tire characteristics, state of wear, inflation, and temperature. Ten percent slip (stretching) and five-degrees yaw (twisting the footprint) are roughly equivalent in magnitude and are close to common optimums. Avoidance of scrubbing to preserve tire life and also to reduce the risk of tire failure is of such importance that conventional brake usage is more on the order of 4 to 5 ft/sec^2 (one-seventh gravity). It appears that manual "feel" is somewhat inexact in determining whether braking is on the scrubbing or no scrubbing side of optimum.

Cornering, while having about the same tangent force available as for braking, is a different matter. The stability and response of the steering system add requirements for tire/pavement reaction reducing the available radial acceleration force. When a vehicle moves in an arc, all tire track curves have the same center either by steering or by forced distribution of the yaw angles of the tires (or combination thereof). Since yaw is the tire lateral load acceptance response to turning, the resultant angular acceleration/deceleration of the aircraft about its vertical axis plus some possible cross connection with motion about the lateral axis can be a potential source of control dynamics problems in negotiating a high speed turn. Whether this actually introduces an operating constraint has not been fully determined but it could very well be the cause of the obvious disfavor with which pilots view high speed turns. Not only do pilots consistently overestimate their speed in a turn but their conventional turn speeds are low enough to keep the radial acceleration down to about 1/14 gravity; i.e., half of the usual braking deceleration. Aircraft design for high speed turnoff design considers lateral accelerations of 0.25G passenger limit, 0.5G gear limit and 0.65G aircraft tip-over as passenger/aircraft limitations (ref. 1) Results of high speed turnoff maneuvers showed peak values of lateral acceleration profiles fall within 90-95 percent passenger comfort limits. The maximum lateral acceleration for the turnoff centerline trail correspond roughly to a side load of 0.18g (Ref. j)

Vehicle Stopped - Brake Locked - Tow Force Appl.

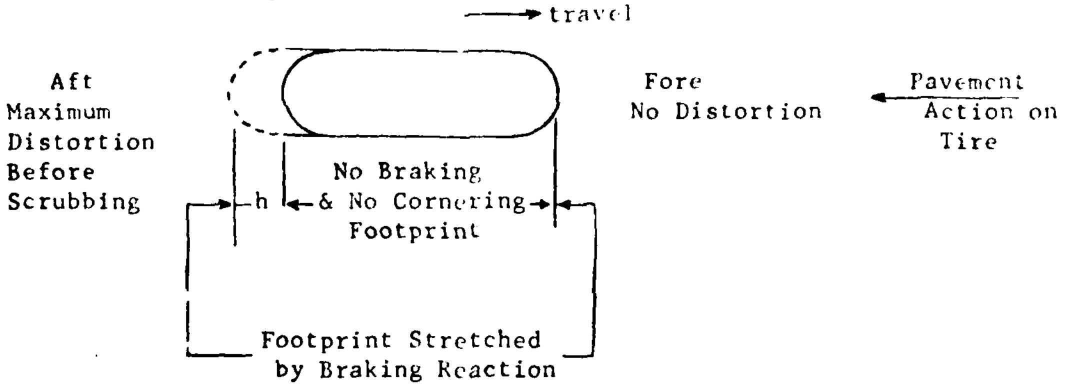


Braking Friction = FB = ah

a = stress/strain ratio
h = distortion

Figure 8a. Friction Model--Footprint--Vehicle Stopped--Locked Brakes

Rolling Tire Under Braking

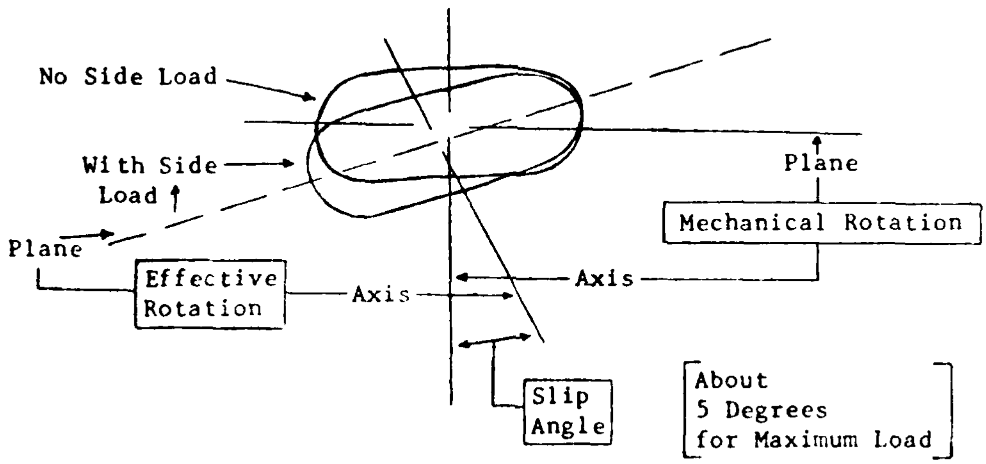


h = maximum tire distortion; e.g., load reaction, before scrubbing begins--dependent on character and contamination of pavement surface and on tire design and condition.

FB = maximum braking force from pavement reaction = $\frac{ah}{2}$

Figure 8b. Friction Model--Footprint--Vehicle Rolling--Under Braking

TIRE "FOOTPRINT" DISTORTION UNDER
SIDE LOAD AS IN CORNERING OR LATERAL GRADE
OR CROSSWIND



SLIP ANGLE under cornering
CRAB ANGLE with lateral grade
& with crosswind

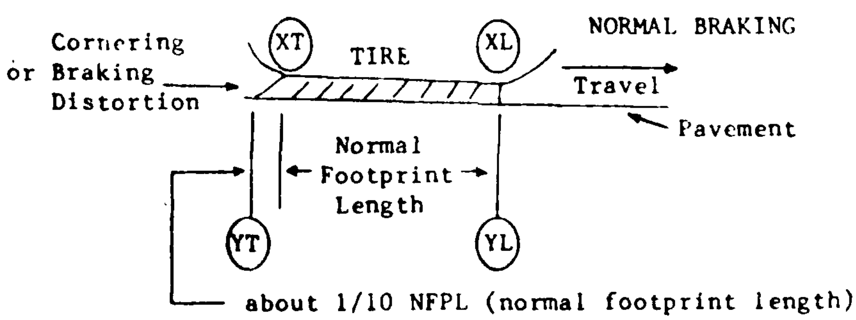
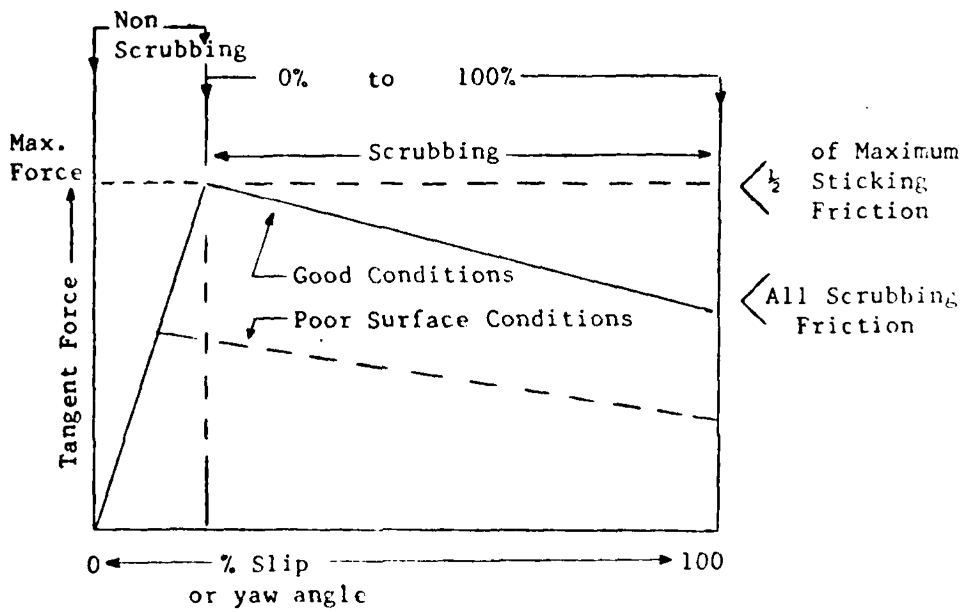


Figure 8c. Friction Model--Footprint--Vehicle Cornering--Side Load



$$\text{Tire \% Slip} = 100 \left[1 - \frac{\text{braked tire peripheral speed}}{\text{relative pavement speed}} \right]$$

Tire Yaw Angle = difference between direction of track and perpendicular to wheel axis.

Note: If ratio of scrubbing to sticking friction is one-half or greater, the available braking or cornering force does <u>not</u> peak at the transition from non-scrubbing to scrubbing but may increase up to full locked skid.
(Similar to Fig. 1.1 ICAO, Airport Services Manual Part 2)

Figure 8d. Friction Model--Rolling & Cornering--
Tangent Force vs. % Slip

It is still possible that each type of air carrier aircraft in current operation has its own limitation on cornering capability. The high speed turn-off tests conducted by NASA, Langley TCV project, showed no problems with high speed steering up to 9 ft/sec^2 lateral accelerations with their 737 aircraft. However, the extent of tire scrubbing assessment was only qualitative and no other aircraft were run.

3.2.2 Human Factors Limitations

The constraints on air carrier aircraft high speed runway exiting and ground maneuvering imposed by involved humans lie in three distinct categories. These are the comfort considerations important to passengers, the skill level of the pilot in executing the designated maneuvers, and the motivational factors responsible for the selection of the actual operating techniques.

Considerable effort has been applied in the air passenger business to avoid alarming the passenger. When sizable changes in attitude, power settings, speed, etc., are required, the emphasis has been placed on making them as smoothly as possible. Smoothness, accomplished by limiting accelerations, shocks, vibration and associated noises, has been very sucessful in making air transportation a comfortable and reassuring experience for even the most timid. Although the landing operation has been smoothed considerably by the current 2--3° approach, a high level of acceleration, both braking and cornering, is still needed to reduce runway occupancy time. The need for appreciable acceleration and the need to avoid a frightening or uncomfortable level required identifying acceptable levels to use as design criteria. Reference (a) found no objection to one quarter gravity lateral accelerations in passenger seats of that era. Half that, 0.13g, was recommended as a design limit level and it has been used widely since. It is generally accepted that body support and restraint figure greatly in safety, comfort, and tolerability levels for acceleration. Accordingly, the comfort levels for lateral acceleration may be much higher for the current cushioned semi-bucket passenger seat designs than those of the '50s. Longitudinal acceleration under braking is easily accommodated by current seat tilt angle design. The human body seems relatively insensitive to fractional magnitude changes in apparent gravity as long as a pitching motion does not result. This may be accomplished by either initial position (partial supine) or restraint. (Some discussion available in references (h & i)

In any event the passenger is most likely to be subject to lower acceleration levels than those commonly experienced in automobiles even with runway occupancy reduced to twenty seconds.

No information could be found which indicated that pilot skill deficiencies could be contributing to the low speed utilization of high speed runway exits. The extensive training, the rigorous skill level checks, and the proficiency maintenance programs in which all air carrier pilots are involved insure that pilots are fully capable of operating the aircraft at maximum performance capability.

Constraints on high performance operation imposed by motivational factors are undoubtedly the governing human factor constraints and they far overshadow all other limitations; even the equipment mechanical factors. The opinion surveys, the motivation study of reference (g),

and numerous other inputs representing pilot attitudes indicate that air carrier pilots are fully motivated to avoid any unnecessary risk or passenger discomfort no matter how small. As long as the air traffic control system delivers arriving aircraft to a runway with no closer than three-mile spacing, there is sufficient separation interval to use turn-off speeds of thirty knots or less. This is true with the 30-degree, 1800-foot radius angled exits that require on the order of 900 ft. (see fig. 4a) travel distance from initial point of curvature to clear of the runway edge. Only in cases where traffic control encourages expediting runway clearance is the exit speed likely to be close to design speed. Other motivational factors which tend to low speed turnoff are likelihood of tire scrubbing with excessive wear, deterioration of steering response with runway contamination, and normal allowance of more than adequate runway deceleration distance. All of these motivational factors combine to impose a fairly standard operational constraint of about one-fourth of the design allowable lateral acceleration. This means that the exit speed is limited to about half of design allowable producing a consistent penalty of 17 to 22 seconds increased runway occupancy time which is fully attributable to human factors.

3.3 Traffic Control Interaction

The capacity of airport runways is primarily controlled by the air traffic control system. Until current separation procedures, separation standards, (aircraft) approach orientation with its low precision (as humanly precise as possible) and tolerance of variance (accordian effect) (with safety in mind) can be improved, the capacity is likely to remain at a (current) low level. As a consequence, independent changes to airport/airside design intended to increase the arrival/departure capacity arelikely to have very little (overall) benefit.

3.3.1 The Approach Delivery Rate

Air traffic control is dedicated to preventing aircraft from getting close enough to each other to compromise safety. As a secondary function, the control facilitates desired travel from one airport to another by observing a set of separation standards and by applying certain separation techniques for enroute, terminal airspace, approach and departure flight operations. Primary and secondary radar monitoring, direct observation, controller/pilot radio and pre-established paths are all used to provide the control essentials. The separations are still based on "eyeball" assessments whether from the controller's view of the radar scope plan position indication or by the pilot's through the wind screen view when on a visual clearance. The net effect is that on busy, predominantly air carrier, airports the average separation between arriving aircraft is simply equal to the average view of pilots and controllers as to what separation is acceptable. With the average separation fixed there is essentially nothing that can be done to change the runway capacity; runway design, exit design, additional exits, even landing procedure changes are all useless. In this situation, a high speed exit is only useful for very gentle turns off the runway and occasionally to allow a hurried but safe exit in front of an occasionally close following airplane.

During the development of capacity and delay measuring techniques a considerable amount of data was collected on arrival/arrival, arrival/departure, departure/arrival, and departure/departure separations at 18 airports with traffic ranging from 10% to 100% G.A. From analysis of these data it can be said that the view of what constitutes acceptable separation (and the resulting of runway capacity) varies considerably from airport to airport, traffic demand, approach speeds, through the window or plan view control, and many other factors. It was quite interesting to note that where demand was high the average separation was nearly equal to the standard minimum and where visual approach clearances were in order the average separation only dropped one-eighth but the scatter approximately doubled over full ATC approaches. (See figure 9.) The indication is that air carrier airport capacity is strictly established by ATC approach control and will not change significantly without some definite changes in the present traffic control system which will allow speeding up the terminal airspace process rate. The metering and sequencing project can possibly utilize computer handling of separation data to improve on the eyeball technique and reduce variance in the separation intervals. Whether the second step, reduced intervals, can be taken will undoubtedly depend upon successful acquisition of an acceptable fail-safe feature.

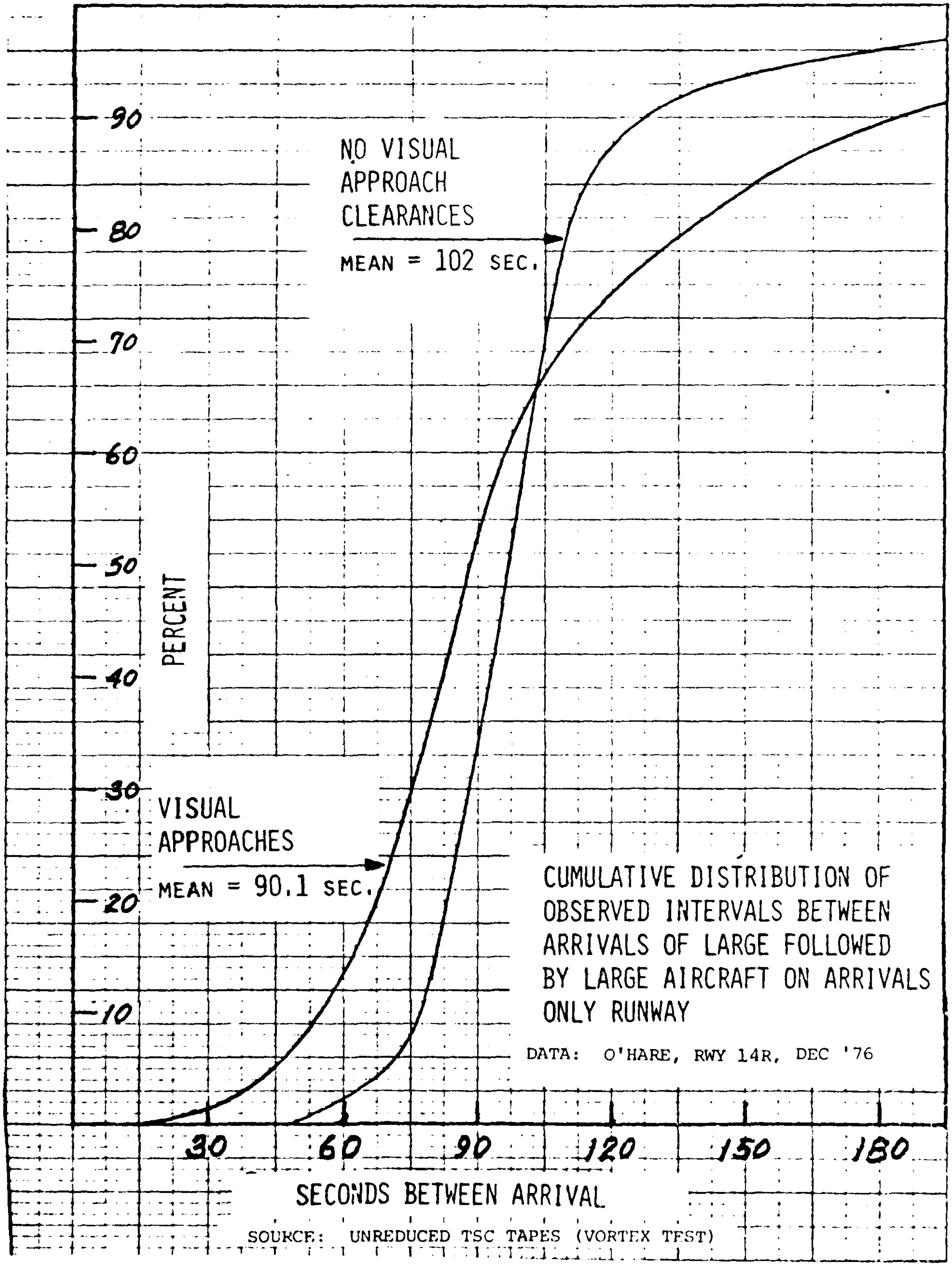
3.3.2 The Separation Standards

The present longitudinal separation standards, while their application is somewhat analogous to use of an elastic measuring tape with tangles in it, provide the stated minimums for radar separation of aircraft. These minimums have been developed out of respect for the potentially dangerous wing tip vortices generated by heavy aircraft span wise air flow. Present techniques to reduce the cautionary separation minimums involve the use of meteorological instrumentation to identify low probability expectations of vortices in the critical time/space window. If the system works, vortex suitable spacing would be required on only a part-time basis. The advantages in average separation reduction would certainly be specific airport peculiar and any resultant improvement in approach process rate would have to be operationally validated.

3.3.3 The Visual Approach Clearance

The visual approach clearance to air carrier airports holds some promise of capacity increasing potential which would open a higher performance level requirement for runway arrival/runway exit operations. To take advantage of this promise some technique would have to be devised and implemented to reduce all separation intervals to the equivalent distribution of the lower 25 percentile. (See figure 9.) This means special attention to identify stragglers and force them to close up their arrival intervals or alert and position them

Figure 9. Interarrival Interval Distribution--Visual & Nonvisual Approaches



while they are far enough out from final approach that the interval can be reduced conveniently and even with increased fuel economy. It follows that if long interarrival intervals can be compressed during visual approach clearances, the same can be accomplished under radar separation if emphasis is placed on greater precision.

3.4 Requirements for High Speed Exits

From the preceding discussions, it should be evident that several difficult achievements must be completed before the 30-degree angle, 1800-foot radius runway turnoff (or any modification thereof) will be consistently used at its full speed capability to realize a significant runway capacity increase.

In the not too distant future the utility of the existing high speed exits may naturally increase as landing operations are standardized and speeded up to accommodate the closer spacing methods developed to meet growing traffic demands. Most airports like O'Hare year after year considered as saturated continue to accept more traffic almost every year. This projected capacity growth possibility by methods not quite clear in the present is believed highly probable. The past has several examples. If this high probability can be accepted, there should be some effort expended to seek out, validate and implement any airport/airside design changes which would support the runway/terminal airspace control capacity growth. Based on the review of both "referenced" and "nonreferenced" (Bibliography), some of the design features worth consideration are as follows:

(a) Superelevation of the runway turnoff.
(b) Establish more direct and higher priority right-of-way between runway and docks.
(c) Revise dock access/egress to reduce conflict. Present finger docks cannot operate at theoretical capacity based on service time due to one-way-at-a-time paths and push back operations.
(d) Revise dock use plans to increase utility and reduce mean service time.
(e) Test and evaluation of larger radius exit curves, using angles of various degrees.
(f) Analysis of current airport geometric standards to reduce maneuvering requirements and taxiing in times.
(g) Test and evaluate exit pavement grooving to permit more positive control capability.

These items above represent one level of requirement for high speed exits and associated airport/airside development which might be considered as applicable to a normal course of events. An added requirement at this same priority level would be the development of assurance that there are actually no aircraft constraints; e.g., test current aircraft and include needed certification requirements for new aircraft.

A considerably higher priority set for high speed exit and airport/airside development projects would be a requirement if an agency-wide positive action program were adopted to develop, test, and implement an improved terminal airspace traffic control system capable of specified significantly higher level process rates. If such an approach is not taken, a low level priority on all airport/airside traffic capacity oriented effort will be adequate to keep pace with ATC capacity growth.

4. Conclusions and Recommendations:

4.1 Conclusions

4.1.1 General

With respect to those questions stated under 1.2 Scope/Purpose on pages 2 and 3 of this report, the following conclusions have been reached.

(a) The information in hand is not adequate for defining an improved standard. Additional study is needed including use of aircraft to determine location, configuration, marking and lighting of such exits.

(b) The existing information indicates a need for better visual cueing, a better defined deceleration and rollout procedure, and that the human factors aspects of both flight crew and passengers must be studied in greater depth including evaluation of responses to actual runway exit trials.

(c) The additional information needed to validate prediction of utility of design changes are those that can be attained from actual aircraft tests with the cabin occupied.

(d) The work that must be done to obtain effective utilization of promising airport/airside designs is covered under 4.2 Recommendations. These can be accomplished by development of a research program that would include the entire airfield geometrics not only runway exits.

Low utilization of high speed exits, although not conclusively shown, appears to be the result of operational use only where and when the need exists to expedite runway clearance. (No one on the tail, too many intermittant crossings and dock location.)

Underutilization of high speed exits also appears to be motivated by desire to avoid any unnecessary risk or passenger discomfort (scrubbing, hard breaking, and lateral deceleration).

4.1.2 Specific

4.1.2.1 The existing standard angled runway exit (commonly called a high speed exit) with a radius of 1800 feet designed for 60 miles per hour is considered safe for use at 60 knots. (Para. 3.1.1)

4.1.2.2 The predominate usage of high speed exits is in the range 20 to 40 knots. This is at considerable variance, both average and scatter, below the safe design speed and results in low exit utility. (Para. 3.1.1)

4.1.2.3 Possible design changes to the standard exit worth considering and devising are (1) improved interconnection with the taxiways and higher priority right-of-way to the docks, and (2) a proven superelevation design and attendant use procedure. (Paras. 3.1.4 and 3.4)

4.1.2.4 Further attention should be given to the interactions, constraints, capabilities, etc., involved in braking, cornering, steering, and tire scrubbing before markedly different operating techniques (not test operations) are considered feasible and practical and used as design criteria. (Para. 3.2, 3.2.1 & 3.2.2)

4.1.2.5 The (low) utility of high speed exits with the related (average) runway occupancy time does not currently limit runway capacity.

Only in rare instances does the essential time to clear the runway exceed the smallest interarrival intervals as determined by the existing approach control practices. Evidence is quite strong that variance in runway occupancy time does not contribute significantly to reducing runway capacity. This is contrary to generally accepted views on the subject, which are based on assuming that runway occupancy time and the interarrival interval are independent variables. The available data, not specifically collected for this purpose, indicate that the two intervals are highly correlated at low interarrival levels.(Para. 3.3.1)

4.1.2.6 Development of equipment and operating techniques to exploit and improve dependence between runway occupancy time and the inter-arrival interval would likely be the most effective of all capacity improvement efforts. (Observation) (Para. 3.3.1)

4.1.2.7 Design changes intended to obtain higher capacity utilization of standard runway exits have very little assurance of success without positive expectations of approach separation, landing techniques, and exiting being specifically revised to increase runway acceptance rates. Arrival/arrival intervals are primary bottlenecks. Arrival/departure, departure/arrival, and departure/departure are secondary and are often avoided by segregated operations at busy airports.(Para. 3.3.1

4.1.2.8 Additional operational data is needed to verify critical parameter values such as correlation between sequential service intervals and to determine if capacity impacting improvements in operating procedure can be effected. Aircraft class segregation, offers considerable promise if improvement efforts are properly oriented. (Para. 3.3.3)

4.1.2.9 Serious consideration should be given to development of equipment and procedures which will allow discarding the concept of the runway as a simple queuing system. Precision deceleration procedures almost independent of magnitude, if accomplished with very high reliability, could produce spectacular increase in capacity. Reliability techniques are available to match the safety levels provided by more than one-at-a-time-on-the-runway axiom. (Observation) (Para. 3.3.3)

4.2 Recommendation

Overall, the study concludes that insufficient data were available to determine if runway angled exits are underutilized and if so, why; what would be the impact of such strategies as aircraft class segregation; what is the relationship of airfield geometry on runway/taxiway utilization, or what is the correlation between sequential service intervals and operating procedures on runway usage time. On the basis of these conclusions, it is recommended that an effort be undertaken to investigate those areas mentioned above and to test, evaluate, and demonstrate improvements found. Such an effort should include:

a. Verification of need of angled exits and identification of factors involved in underutilization.

b. Relationships of total airfield geometry as a factor to angled exit usage.

c. Investigate human factors aspects of exit utilization including location, configuration, visual aids, pavement surface condition, aircraft/crew operational behavior/capability, passenger acceptance and aircraft ground instrumentation requirements.

d. Development of criteria or models that would identify the location and configuration of exits needed on-site specific bases including changes necessary to existing exits to accommodate planned usage.

f. Investigate work being done by NASA Terminal Configured Vehicle Program Office to include results of their tests.

g. Investigate runway exit configurations and airfield geometrics in use or planned by foreign and civil and military organizations.

h. Include in any effort airline and airline pilot consultation and equipment where possible to ensure that operational procedures and human factors are considered. Laboratory tests should include airline aircraft simulation as well as instrumented aircraft.

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